# INSECT RESIDUE CONTAMINATION ON WING LEADING EDGE SURFACES: A MATERIALS INVESTIGATION FOR MITIGATION

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## Introduction

Flight tests have shown that residue from insect strikes on aircraft wing leading edge surfaces may induce localized transition of laminar to turbulent flow.[1] The highest density of insect populations have been observed between ground level and 153 m during light winds (2.6 – 5.1 m s$^{-1}$), high humidity, and temperatures from 21 – 29 °C.[2] At a critical residue height, dependent on the airfoil and Reynolds number, boundary layer transition from laminar to turbulent results in increased drag and fuel consumption. Although this represents a minimal increase in fuel burn for conventional transport aircraft, future aircraft designs will rely on maintaining laminar flow across a larger portion of wing surfaces to reduce fuel burn during cruise (**Figure 1**). Thus, insect residue adhesion mitigation is most critical during takeoff and initial climb to maintain laminar flow in fuel-efficient aircraft configurations. Several exterior treatments investigated to mitigate insect residue buildup (e.g., paper, scrapers, surfactants, flexible surfaces) have shown potential; however, implementation has proven to be impractical. Current research is focused on evaluation of wing leading edge surface coatings that may reduce insect residue adhesion. Initial work under NASA's Environmentally Responsible Aviation Program focused on evaluation of several commercially available products (commercial off-the-shelf, **COTS**), polymers, and substituted alkoxy silanes that were applied to aluminum (Al) substrates. Surface energies of these coatings were determined from contact angle data and were correlated to residual insect excrescence on coated aluminum substrates using a custom-built "bug gun." Quantification of insect excrescence surface coverage was evaluated by a series of digital photographic image processing techniques.
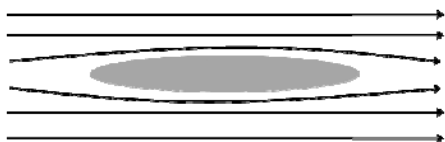


**Figure 1.** Schematic of laminar flow.

## Experimental

**Materials**. Al 1100 and Al 2024 surfaces were wiped with ethanol using a dust-free laboratory cloth prior to any analysis or surface treatment. Several commercially available materials were purchased for testing. These materials, referred to hereafter as **COTS1** – **COTS4** were applied according to the manufacturers' instructions. Heptadecafluoro-1,1,2,2-tetrahydrodecyl-triethoxysilane (**Hydrophobic**) and methoxy(polyethyleneoxy)propyl trimethoxysilane (**Hydrophilic**) were purchased from Gelest, Inc. and used as received. These coatings were applied by spray coating after acid hydrolysis. Additional samples were generated with a combined application of **Hydrophobic** and **Hydrophilic** and will be referred to as **Mixed**. Poly(2-hydroxyethyl methacrylate) (**pHEMA**) was purchased from Sigma Aldrich, Inc. and applied by spray coating.

**Contact Angle Goniometry**. Contact angle goniometry was performed using a First Ten Angstroms, Inc. model FTA 1000B. Sessile drop contact angles were measured at 23°C for each sample using a 5 μL drop of either water or ethylene glycol, or a 2 μL drop of methylene iodide. Five measurements were made with each liquid. Interfacial tension measurements of a suspended drop of each liquid were made prior to experimentation to verify the purity of the liquid and precision of the focused image. Contact angles were determined by drop shape analysis. Additionally, contact angle measurements were performed with an insect cell-growth medium (Grace's) designed to simulate insect (e.g., Australian emperor gum moth) hemolymph.

**Insect Adhesion Testing.** Insect adhesion testing was conducted using a custom-built "bug gun" and bait crickets (**Figure 2**). The coatings were applied to thin pieces of Al 6061 that were subsequently mounted onto 5 cm diameter PVC pipe to simulate a wing leading edge contour. The bug gun was constructed from large diameter plastic tubing pipe and was powered by a 10 cm diameter, squirrel cage fan operating at 3160 rpm. The coated Al substrates were located approximately 2.5 cm from the bug gun muzzle. Testing was conducted at ambient temperature (~22 °C) and 43 – 51% relative humidity. Approximately 60 mL of bait crickets were poured into the bug gun hopper, located directly above the fan, per test run. The crickets passed through the fan resulting in partial fracturing of insect exoskeletons. High speed photographs were acquired during the test and static photos were collected after the test was completed. Each coating was tested twice. The exit velocity of the cricket and cricket pieces ranged from 5 to 46 km h$^{-1}$ with an average velocity of 21 km h$^{-1}$.
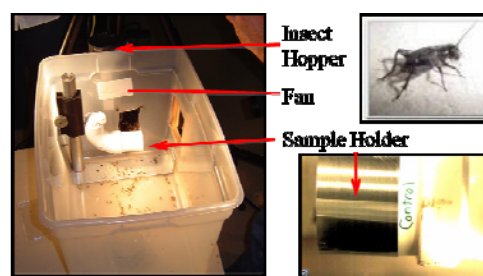


**Figure 2.** Insect impact facility and a picture of the bait crickets.

**Image Analysis of Insect Adhesion Tested Specimens.** Upon completion of insect adhesion testing, the Al 6061 test specimens were analyzed to determine the percentage of insect residue surface coverage. Photographs of the surfaces captured the fluorescence of the insect residue excited by a UV flash bulb. The image was cropped and the green plane extracted using XnView to differentiate the insect residue from the substrate surface. The resultant images were processed using IMAQ Vision Builder by running a series of filter scripts, converting the images to binary, and finally calculating the relative percentages of black and white pixel areas. Insect residue percent surface coverage was calculated as the ratio of black (residue) to white (substrate) surface area.

## Results and Discussion

**Surface Coating and Characterization.** Insect hemolymph has long been recognized to adhere to exposed surfaces; however, there are only a few literature examples of correlation between surface chemistry and degree of insect hemolymph adhesion.[3] Therefore, Al surfaces were coated with a variety of materials resulting in an array of surface chemistries to further study this relationship. Although the exact composition of the COTS materials was not disclosed, the general chemical composition of the materials was discerned. The chemistries evaluated in this work included an aliphatic, fluorinated polymer (**COTS1**), substituted siloxanes (**COTS2** and **COTS3**), polyvinyl alcohol (**COTS4**), a fluorinated, silane coupling agent (**Hydrophobic**), an ethylene glycol silane coupling agent (**Hydrophilic**), and a hydroxyl-functionalized methacrylate (**pHEMA**). These coatings were controllably applied to the Al surfaces to minimize sample topography variation. The surfaces were then characterized by contact angle goniometry using water, ethylene glycol, and methylene iodide. Grace's insect media was also investigated, however the contact angle values observed with this liquid were comparable to water for several substrates. The surface energy ($\gamma$) of each sample was determined using the van Oss-Chaudhury-Good theory to delineate contributions to surface energy from specific intermolecular interactions: dispersive ($\gamma^d$) and polar ($\gamma^p$).[4] The polar interactions are further separated into Lewis basic ($\gamma^-$) and acidic ($\gamma^+$) contributions.

**Table 1.** Surface energies of coated Al 2024 samples.

| | mJ m$^{-2}$ | | | | |
|---|---|---|---|---|---|
| | $\gamma^d$ | $\gamma^p$ | $\gamma^-$ | $\gamma^+$ | $\gamma^{tot}$ |
| Coating[a] | Dispersive | Polar | Basic | Acidic | Total |
| COTS1 | 9.2[b] | 0.0 | 1.0 | 0.0 | 9.2 |
| Hydrophobic | 12.0 | 0.9 | 0.8 | 0.3 | 12.9 |
| COTS2 | 14.3 | 0.3 | 2.4 | 0.0 | 14.5 |
| Mixed | 21.2 | 0.3 | 8.8 | 0.0 | 21.5 |
| COTS3 | 27.8 | 0.9 | 3.4 | 0.1 | 28.6 |
| *Control* | *33.5* | *1.1* | *6.1* | *0.0* | *34.6* |
| Hydrophilic | 41.4 | 1.8 | 27.1 | 0.0 | 43.1 |
| COTS4 | 33.2 | 11.8 | 45.7 | 0.8 | 45.0 |
| pHEMA | 41.3 | 5.0 | 24.4 | 0.3 | 46.3 |

[a]The coatings are arranged in increasing total surface energy.
[b]Surface energy standard deviation values were typically 10%.

The surface energies determined for the coated Al 2024 samples correlated well with the known surface chemistries and impact of chemical functionalities on surface energy. For example, fluorinated aliphatic materials exhibit nominal contributions to surface energy from dispersive interactions and negligible contributions from polar interactions (i.e., Teflon®). This was demonstrated by the **COTS1** and **Hydrophobic** surfaces, which were found to have the two lowest surface energies. Similarly hydroxy and alkoxy functionalities contributed significantly to both dispersive and basic surface energy components for the **Hydrophilic**, **COTS4**, and **pHEMA** surfaces, all of which contain these functionalities. The control surface, an Al sample that was cleaned with ethanol prior to analysis, exhibited a surface energy between these two extremes indicating that there was a residual layer of contaminant (water, organic, etc.) on the Al surface. A pristine Al surface should be completely "wetted" by all of the test solvents.

**Insect Adhesion Testing.** Thin Al 6061 samples were mounted on PVC pipe sections and subjected to impact from bait crickets, whole and segmented, in order to evaluate the adhesion of insect excrescence. The bait crickets were poured into the hopper of the bug gun in a single step to simulate an insect strike upon an aircraft surface. The insects were observed to impact the test specimen at normal and glancing angles resulting in a myriad of results. In most cases, insect impact on the surface did not cause further disruption of the exoskeleton (**Figure 3**).
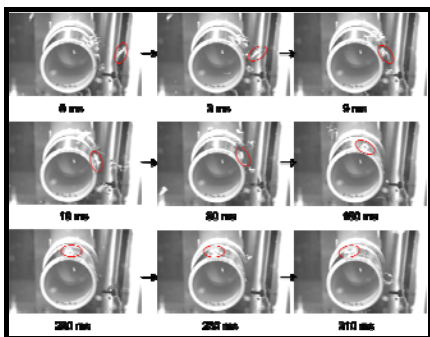


**Figure 3.** High speed video images collected during an insect adhesion test.

Segmented cricket pieces were found to consist of two different types, objects with exoskeleton and objects consisting only of hemolymph. For the latter, impact on the surface resulted in adhesion with nominal additional motion. Cricket pieces with exoskeleton intact (e.g., a leg) were observed to either temporarily or permanently adhere to the test surface. This appeared to depend on whether there was hemolymph available for adhesion promotion either from previous impacts or from the cricket piece itself. An example of a control Al 6061 surface after insect adhesion testing is shown in **Figure 4**.

The average exit velocity of crickets from the bug gun (21 km h$^{-1}$) was significantly lower than the average velocity of commercial aircraft at takeoff and landing (240 – 285 km h$^{-1}$). The threshold rupture speed of an insect was calculated to be approximately 76 km h$^{-1}$.[5] The difference in speed was compensated by segmenting the insects in the fan prior to impact. A second

generation bug-gun is currently being constructed with velocity capabilities better aligned to aircraft velocities and that of Croom, et al.(ref.5)



**Figure 4.** Al 6061 sample after insect adhesion testing.

Once the insect adhesion test was completed, static images of the surfaces were collected using a UV flash bulb. The insect excrescence was fluorescent, enabling image processing to separate surface area with and without insect excrescence present. The insect residue surface coverage was calculated as the ratio of area covered by insect excrescence to the total surface area (**Figure 5**). Surprisingly, the surfaces with the lowest surface energy did not yield the lowest insect residue surface coverage. In fact, the control Al 6061 surface performed comparably, if not better, than all of the coatings tested, except for **COTS2**.
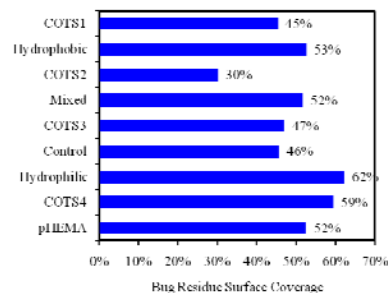


**Figure 5.** Insect residue surface coverage on the coated Al 6061 samples.

## Conclusions

Commercially available materials were evaluated to determine surface energy and insect adhesion properties in an effort to elucidate a correlation between surface chemistry and insect adhesion. Although the surface energy determined for the materials tested here followed the expected trend based on chemical structure, the magnitude of insect adhesion was found to be only modestly sensitive to surface energy. Surfaces with lower surface energies did exhibit a reduction in insect adhesion, but not to the degree required for effective insect adhesion mitigation. These results indicate that commercially available materials provide a nominal improvement compared to the bare Al 6061 surface. Thus, novel approaches need to be undertaken to mitigate insect adhesion to aircraft surfaces and this is currently underway. The photographic image analysis was successful at determining the amount of insect residue surface coverage, but not the height or topography of the insect residue deposits. 3D image analysis techniques are currently being evaluated to determine these properties.

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